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Measurement of Time-Dependent CP-Violating Asymmetries in $B^0 \to \phi K_S^0$, $K^+K^-K_S^0$ and $\eta' K_S^0$ Decays

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Abstract

We present an improved measurement of CP-violation parameters in $B^0 \to \phi K_S^0$, $K^+K^-K_S^0$, and $\eta' K_S^0$ decays based on a 140 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. One neutral B meson is fully reconstructed in one of the specified decay channels, and the flavor of the accompanying B meson is identified from its decay products. CP-violation parameters for each of the three modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two B decays. We find that the observed CP asymmetry in the $B \to \phi K_S^0$ decay differs from the standard model (SM) expectation by 3.5 standard deviations, while the other cases are consistent with the SM.

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In the standard model (SM), CP violation arises from an irreducible phase, the Kobayashi-Maskawa (KM) phase [1], in the weak-interaction quark-mixing matrix. In particular, the SM predicts CP asymmetries in the time-dependent rates for B^0 and $\overline{B}^0$ decays to a common CP eigenstate f_{CP} [2]. Recent measurements of the CP-violation parameter $\sin 2\phi_1$ by the Belle [3] and BaBar [4] collaborations established CP violation in $B^0 \to J/\psi K_S^0$ and related decay modes [5], which are governed by the $b \to c\bar{c}s$ transition, at a level consistent with KM expectations.

Despite this success, many tests remain before one can conclude that the KM phase is the only source of CP violation. The $B^0 \to \phi K_S^0$ decay, which is dominated by the $b \to s\bar{s}s$ transition, is sensitive to new CP-violating phases from physics beyond the SM [6]. The other charmless decays $B^0 \to K^+K^-K_S^0$ and $B^0 \to \eta' K_S^0$, which are mediated by $b \to s\bar{s}s$, $s\bar{u}u$ and $s\bar{d}d$ transitions, also provide additional information. Since the SM predicts that measurements of CP violation in these charmless modes should also yield $\sin 2\phi_1$ to a good approximation [7, 8], a significant deviation in the time-dependent CP asymmetry in these modes from what is observed in $b \to c\bar{c}s$ decays would be evidence for a new CP-violating phase.

In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP} f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a final state f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by [2]

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q \cdot \Big[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\Big]\Big\}, \tag{1}$$

where τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 ($\overline{B}^0$). $\mathcal{S}$ and $\mathcal{A}$ are CP-violation parameters; to a good approximation, the SM predicts $\mathcal{S} = -\xi_f \sin 2\phi_1$, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states, and $\mathcal{A} = 0$ for both $b \to c\bar{c}s$ and $b \to s\bar{s}s$ transitions. The present world-average $\mathcal{S}$ value obtained from previous measurements by the Belle [9] and BaBar [10] collaborations is within 2σ of the SM expectation for $B^0 \to \eta' K_S^0$ and $K^+K^-K_S^0$, while a 2.7σ deviation exists for $B^0 \to \phi K_S^0$. Measurements with a larger data sample are required to resolve this difference.

Belle's previous measurement for $B^0 \to \phi K_S^0$, $K^+K^-K_S^0$ and $\eta' K_S^0$ was based on a 78 fb^{-1} data sample containing 85 million $B\overline{B}$ pairs. In this Letter, we report an improved measurement incorporating an additional 62 fb^{-1} for a total of 140 fb^{-1} (152 million $B\overline{B}$ pairs). At the KEKB energy-asymmetric e^+e^- (3.5 on 8.0 GeV) collider [11], the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and $\overline{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq (z_{CP} - z_{\rm tag})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The Belle detector [12] is a large-solid-angle spectrometer that includes a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

We reconstruct B^0 decays to ϕK_S^0 and $\eta' K_S^0$ final states for $\xi_f = -1$, and $B^0 \to K^+K^-K_S^0$ decays that are a mixture of $\xi_f = +1$ and -1. K^+K^- pairs that are consistent with $\phi \to K^+K^-$ decay are excluded from the $B^0 \to K^+K^-K_S^0$ sample. We find that the

$K^+K^-K_S^0$ state is primarily $\xi_f = +1$; a measurement of the $\xi_f = +1$ fraction with a 140 fb^{-1} data set yields $1.03 \pm 0.15(\mathrm{stat}) \pm 0.05(\mathrm{syst})$, which is consistent with the previous result [8]. In the following determination of $\mathcal{S}$ and $\mathcal{A}$, we fix $\xi_f = +1$ for this mode. The intermediate meson states are reconstructed from the following decay chains: $\eta' \to \rho^0(\to \pi^+\pi^-)\gamma$ or $\eta' \to \pi^+\pi^-\eta(\to \gamma\gamma)$, $K_S^0 \to \pi^+\pi^-$, and $\phi \to K^+K^-$. Candidate $K_S^0 \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays are selected with the same criteria as those used for the previous branching fraction measurements [13]. The K_S^0 selection is slightly changed from the previously published CP asymmetry measurement [9] to improve the K_S^0 purity.

Since the ϕ meson selection is effective in reducing background events, we impose only minimal kaon-identification requirements. We use more stringent kaon-identification requirements to select non-resonant K^+K^- candidates for the $B^0 \to K^+K^-K_S^0$ decay [8]. We reject K^+K^- pairs that are consistent with $D^0 \to K^+K^-$, $\chi_{c0} \to K^+K^-$, or $J/\psi \to K^+K^-$ decay. $D^+ \to K_S^0K^+$ candidates are also removed. We use the same η' selection criteria as those used in our previously published analyses [9, 14].

For reconstructed $B \to f_{CP}$ candidates, we identify B meson decays using the energy difference $\Delta E \equiv E_B^{\mathrm{cms}} - E_{\mathrm{beam}}^{\mathrm{cms}}$ and the beam-energy constrained mass $M_{\mathrm{bc}} \equiv \sqrt{(E_{\mathrm{beam}}^{\mathrm{cms}})^2 - (p_B^{\mathrm{cms}})^2}$, where $E_{\mathrm{beam}}^{\mathrm{cms}}$ is the beam energy in the cms, and E_B^{cms} and p_B^{cms} are the cms energy and momentum of the reconstructed B candidate, respectively. The B meson signal region is defined as $|\Delta E| < 0.06$ GeV for $B^0 \to \phi K_S^0$, $|\Delta E| < 0.04$ GeV for $B^0 \to K^+K^-K_S^0$, $|\Delta E| < 0.06$ GeV for $B^0 \to \eta'(\to \rho\gamma)K_S^0$, or -0.10 GeV $< \Delta E < 0.08$ GeV for $B^0 \to \eta'(\to \pi^+\pi^-\eta)K_S^0$, and 5.27 GeV$/c^2 < M_{\mathrm{bc}} < 5.29$ GeV$/c^2$ for all decays. In order to suppress background from the $e^+e^- \to u\overline{u}$, $d\overline{d}$, $s\overline{s}$, or $c\overline{c}$ continuum, we form signal and background likelihood functions, $\mathcal{L}_{\mathrm{S}}$ and $\mathcal{L}_{\mathrm{BG}}$, from a set of variables that characterize the event topology, and impose thresholds on the likelihood ratio $\mathcal{L}_{\mathrm{S}}/(\mathcal{L}_{\mathrm{S}} + \mathcal{L}_{\mathrm{BG}})$ [13]. The threshold value depends both on the decay mode and on the flavor-tagging quality.

The b-flavor of the accompanying B meson is identified from inclusive properties of particles that are not associated with the reconstructed $B^0 \to f_{CP}$ decay [3]. We use two parameters, q and r, to represent the tagging information. The first, q, is already defined in Eq. (1). The parameter r is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six r intervals. The wrong tag fractions for the six r intervals, w_l $(l = 1, 6)$, and differences between B^0 and $\overline{B}^0$ decays, Δw_l, are determined from the data; we use the same values that were used for the $\sin 2\phi_1$ measurement [15].

The decay vertices of B^0 mesons are reconstructed using tracks that have enough SVD hits. The vertex position for the f_{CP} decay is reconstructed using charged tracks excluding pions from the K_S^0 decays. The f_{tag} vertex determination remains unchanged from the previous publication [9], and is described in detail elsewhere [16].

After flavor tagging and vertex reconstruction, we obtain the numbers of $B^0 \to f_{CP}$ candidates, N_{ev}, listed in Table I. Figure 1 shows the M_{bc} distributions for the reconstructed B candidates that have ΔE values within the signal region. We use events outside the signal region as well as a large MC sample to study the background components. The dominant background comes from continuum events. In addition, according to MC simulation, there is a small ($\sim 3\%$) contamination from $B\overline{B}$ background events in $B^0 \to \eta' K_S^0$ $(\eta' \to \rho^0\gamma)$. The contributions from $B\overline{B}$ events are smaller for other decay modes. The contamination of $K^+K^-K_S^0$ events in the ϕK_S^0 sample $(7.2 \pm 1.7\%)$ is also small. Finally, backgrounds from the $B^0 \to f_0(980)K_S^0$ decay, which has the opposite CP eigenvalue to ϕK_S^0, are found to be small $(1.6^{+1.9}_{-1.5}\%)$. The influence of these backgrounds is treated as a source of systematic

TABLE I: The numbers of reconstructed $B^0 \to f_{CP}$ candidates used for $\mathcal{S}$ and $\mathcal{A}$ determination, $N_{\rm ev}$, and the estimated signal purity in the ΔE-$M_{\rm bc}$ signal region for each f_{CP} mode.

Mode	ξ_f	$N_{\rm ev}$	Purity
ϕK_S^0	-1	106	0.64 ± 0.10
$K^+K^-K_S^0$	$+1(100\%)$	361	0.55 ± 0.05
$\eta' K_S^0$	-1	421	0.58 ± 0.05

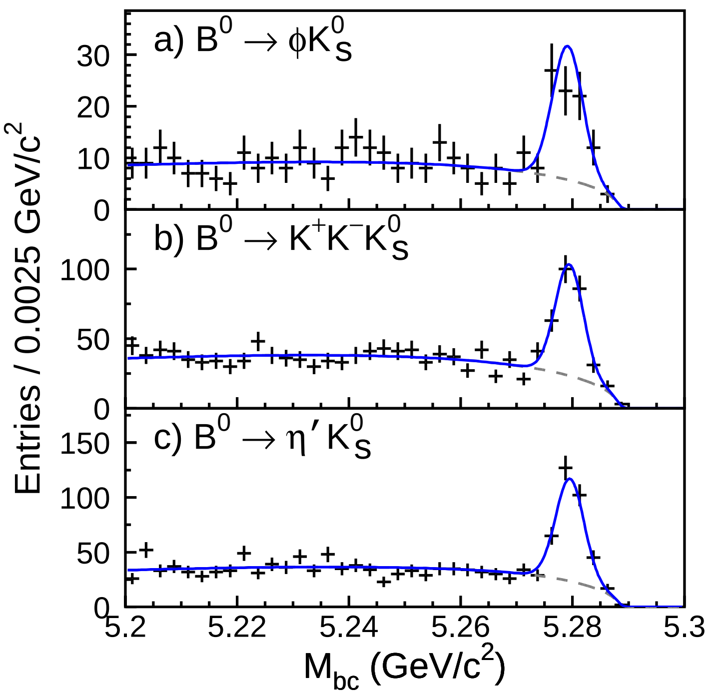

FIG. 1: The $M_{\rm bc}$ distributions for (a) $B^0 \to \phi K_S^0$, (b) $B^0 \to K^+K^-K_S^0$, and (c) $B^0 \to \eta' K_S^0$ within the ΔE signal region. Solid curves show the fit to signal plus background distributions, and dashed curves show the background contributions. The fit functions are the same as those used in the previous publication [9].

uncertainty.

We determine $\mathcal{S}$ and $\mathcal{A}$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) expected for the signal distribution, $\mathcal{P}_{\rm sig}(\Delta t; \mathcal{S}, \mathcal{A}, q, w_l, \Delta w_l)$, is given by Eq. (1) incorporating the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\rm sig}(\Delta t)$ [15], which takes into account the finite vertex resolution. We determine the following likelihood value for each event:

$$\begin{aligned} P_i \; = \; & (1-f_{\rm ol}) \int_{-\infty}^{\infty} \Big[f_{\rm sig} \mathcal{P}_{\rm sig}(\Delta t') R_{\rm sig}(\Delta t_i - \Delta t') \\ & + \; (1-f_{\rm sig}) \mathcal{P}_{\rm bkg}(\Delta t') R_{\rm bkg}(\Delta t_i - \Delta t') \Big] d(\Delta t') \\ & + \; f_{\rm ol} P_{\rm ol}(\Delta t_i) \end{aligned} \qquad (2)$$

TABLE II: Results of the fits to the Δt distributions. The first errors are statistical and the second errors are systematic. The third error for the $K^+K^-K_S^0$ mode arises from the uncertainty in the fraction of the CP-odd component.

Mode	$-\xi_f\mathcal{S}$ (= $\sin 2\phi_1$ in the SM)	$\mathcal{A}$ (= 0 in the SM)
ϕK_S^0	$-0.96 \pm 0.50^{+0.09}_{-0.11}$	$-0.15 \pm 0.29 \pm 0.07$
$K^+K^-K_S^0$	$+0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0.00}$	$-0.17 \pm 0.16 \pm 0.04$
$\eta' K_S^0$	$+0.43 \pm 0.27 \pm 0.05$	$-0.01 \pm 0.16 \pm 0.04$

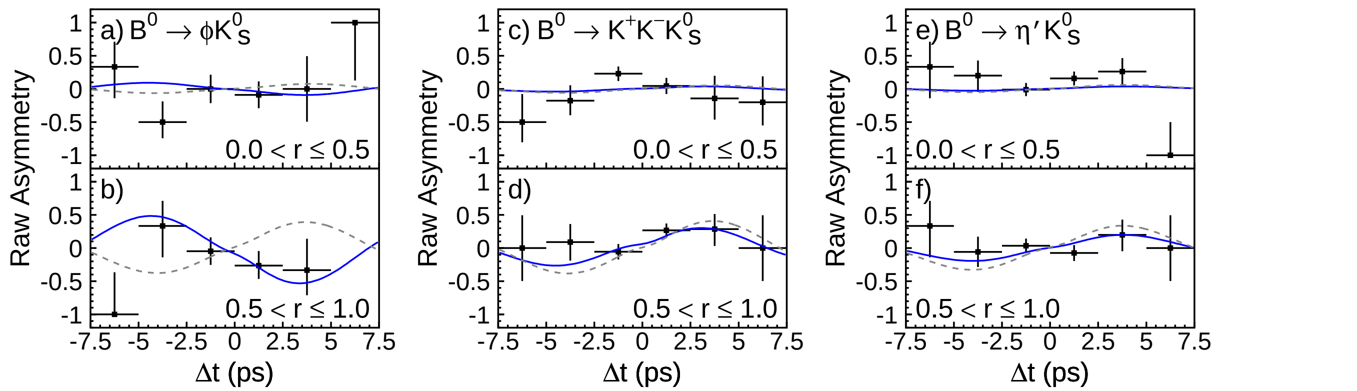

FIG. 2: (a) The asymmetry, A, in each Δt bin for $B^0 \to \phi K_S^0$ with $0 < r \leq 0.5$, (b) with $0.5 < r \leq 1.0$, (c) for $B^0 \to K^+K^-K_S^0$ with $0 < r \leq 0.5$, (d) with $0.5 < r \leq 1.0$, (e) for $B^0 \to \eta' K_S^0$ with $0 < r \leq 0.5$, and (f) with $0.5 < r \leq 1.0$, respectively. The solid curves show the result of the unbinned maximum-likelihood fit. The dashed curves show the SM expectation with $\sin 2\phi_1 = +0.731$ and $\mathcal{A} = 0$.

where $P_{\rm ol}(\Delta t)$ is a broad Gaussian function that represents an outlier component with a small fraction $f_{\rm ol}$. The signal probability $f_{\rm sig}$ depends on the r region and is calculated on an event-by-event basis as a function of ΔE and $M_{\rm bc}$ [9]. $\mathcal{P}_{\rm bkg}(\Delta t)$ is a PDF for background events, which is modeled as a sum of exponential and prompt components, and is convolved with a sum of two Gaussians $R_{\rm bkg}$. All parameters in $\mathcal{P}_{\rm bkg}(\Delta t)$ and $R_{\rm bkg}$ are determined by the fit to the Δt distribution of a background-enhanced control sample [17]; i.e. events away from the ΔE-$M_{\rm bc}$ signal region. We fix τ_{B^0} and Δm_d at their world-average values [18]. The only free parameters in the final fit are $\mathcal{S}$ and $\mathcal{A}$, which are determined by maximizing the likelihood function $L = \prod_i P_i(\Delta t_i; \mathcal{S}, \mathcal{A})$ where the product is over all events. Table II gives the fit values of $-\xi_f\mathcal{S}$ and $\mathcal{A}$. These results are consistent with the previous results [9] and supersede them. We obtain values consistent with the present world average of $\sin 2\phi_1 = +0.731 \pm 0.056$ [18] in the $B^0 \to K^+K^-K_S^0$ and $\eta' K_S^0$ decays, while a negative value is observed in $B^0 \to \phi K_S^0$ decay.

We define the raw asymmetry in each Δt bin by $A \equiv (N_{q\xi_f=-1} - N_{q\xi_f=+1})/(N_{q\xi_f=-1} + N_{q\xi_f=+1})$, where $N_{q\xi_f=+1(-1)}$ is the number of observed candidates with $q\xi_f = +1(-1)$. Figures 2(a-f) show the raw asymmetries in two regions of the flavor-tagging parameter r. While the numbers of events in the two regions are similar, the effective tagging efficiency is much larger and the background dilution is smaller in the region $0.5 < r \leq 1.0$. The observed CP asymmetry for $B^0 \to \phi K_S^0$ in the region $0.5 < r \leq 1.0$ [Fig. 2(b)] indicates the difference

from the SM expectation (dashed curve). Note that these projections onto the Δt axis do not take into account event-by-event information (such as the signal fraction, the wrong tag fraction and the vertex resolution), which is used in the unbinned maximum-likelihood fit.

Fits to the same samples with $\mathcal{A}$ fixed at zero yield $-\xi_f \mathcal{S} = -0.99 \pm 0.50$(stat) for $B^0 \to \phi K_S^0$, $-\xi_f \mathcal{S} = +0.54 \pm 0.24$(stat) for $B^0 \to K^+K^-K_S^0$, and $-\xi_f \mathcal{S} = +0.43 \pm 0.27$(stat) for $B^0 \to \eta' K_S^0$. Applying the same fit procedure, we also obtain $\mathcal{S} = -0.09 \pm 0.26$(stat), $\mathcal{A} = +0.18 \pm 0.20$(stat) for $B^+ \to \phi K^+$ decay and $\mathcal{S} = +0.10 \pm 0.14$(stat), $\mathcal{A} = -0.04 \pm 0.09$(stat) for $B^+ \to \eta' K^+$ decay. Both results for the $\mathcal{S}$ term are consistent with no CP asymmetry, as expected.

The dominant sources of systematic error for the $B^0 \to \phi K_S^0$ mode are a possible fit bias for the input $\mathcal{S}$ value near the physical boundary ($^{+0.06}_{-0.00}$ for $\mathcal{S}$), the uncertainties in the $B^0 \to K^+K^-K_S^0$ and $f_0(980)K_S^0$ background fractions ($^{+0.00}_{-0.08}$ for $\mathcal{S}$ and ± 0.04 for $\mathcal{A}$), in the other background fractions (± 0.05 for $\mathcal{S}$ and ± 0.04 for $\mathcal{A}$), and in the vertex reconstruction (± 0.02 for $\mathcal{S}$ and ± 0.05 for $\mathcal{A}$). Other contributions come from uncertainties in the background Δt distribution, wrong tag fractions, τ_{B^0}, and Δm_d. We add each contribution in quadrature to obtain the total systematic uncertainty. Systematic uncertainties from these sources are also examined for the other modes. We find that the dominant sources are uncertainties from the background fractions and from the vertex reconstruction.

We use the Feldman-Cousins frequentist approach [19] to determine the statistical significance of the observed deviation from the SM expectation in $B^0 \to \phi K_S^0$. The procedure is described in detail elsewhere [20]. From 1-dimensional confidence intervals for $\mathcal{S}$ with $\mathcal{A}$ set at zero, the case with $\mathcal{S} = +0.731$ is ruled out at 99.95% confidence level, equivalent to 3.5σ significance for Gaussian errors. As a cross check, we varied the selection criteria for the $B^0 \to \phi K_S^0$ decay and repeated the analysis. We find no sizable change in the significance.

In summary, we have performed improved measurements of CP-violation parameters for $B^0 \to \phi K_S^0$, $K^+K^-K_S^0$ and $\eta' K_S^0$ decays. These charmless decays are sensitive to possible new CP-violating phases. Our results for $B^0 \to \eta' K_S^0$ and $K^+K^-K_S^0$ are consistent with those obtained for $B^0 \to J/\psi K_S^0$ and other decays governed by the $b \to c\bar{c}s$ transition. On the other hand, a 3.5σ deviation is observed for $B^0 \to \phi K_S^0$. The result suggests that there is a large CP-violating phase in its decay amplitude, which cannot be explained by the SM.

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